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Plastics streams in Germany—an analysis of production, consumption and waste generation

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Abstract

This paper traces plastics streams through the German economy. A material flow simulation model is used to analyze the production of plastics products, their use and residence times in the economy and finally to calculate the present and future amounts of waste. We find that there is an indirect net export of plastics products incorporated in final products which amounts to 3–6% of domestic consumption. Residence times of plastics products range from a few months to 30 years and more, with the weighted average amounting to 14 years. In Germany, total post-consumer plastics waste will rise from 4.6 Mt in 1995 to 6.2–7.2 Mt in 2005 and could easily reach a value in the range of 12–14 Mt in 2025. At the same time, the accumulation of plastics in the economy will increase from about 72 Mt in 1995 to 180 Mt in 2025 in the business-as-usual scenario. The share of waste from long-lived products will continue to grow in the next decades. For polyolefins, PVC and polystyrene in plastics waste, we expect that the total amounts will more than double within the next 25 years. Analyses as presented in this paper can help to establish strategic waste management policies.

Keywords: Material flow analysis (MFA); Forecast; Plastics sector; Plastics waste; Accumulation

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1. Introduction

Germany is the world's third largest producer and consumer of plastics after the U.S. and Japan [1]. German consumption of primary plastics grew from approx. 6.0 Mt in 1976 to 9.1 Mt in 1995 which is equivalent to an increase of about 2.2% per year[1]. The consumption of plastics products is even more dynamic: for the same period, it increased from 4.7 to 9.6 Mt, i.e. 3.8% per year [2–4]. It is uncertain how this trend will develop in the medium or long term. Nevertheless it is quite probable that the consumption of plastics products in absolute terms will continue to grow rapidly.

Increased consumption of plastics results in a larger accumulation in the economy, i.e. plastics are stocked e.g. in households, cars and buildings. On the other hand, the plastics are released as waste when the service period of these goods is over. Increasing plastics consumption will lead to higher plastics waste volumes. Planning of future waste management systems should take these into account as well as changes in waste composition by materials and products (sources). The main goals of this article are to estimate the current and future amount of post-consumer plastics waste and to analyze the development of stocks in the German society. There are different approaches to investigate material flows in past and present and to make forecasts for the future. One of the methods is to include these physical streams in a macroeconomic model [5], another is material flow analysis (MFA). MFAs on plastics waste do exist, but those available for Germany are either confined to a certain type of plastic [6,7] or they analyze the situation in the recent past [8]. In this paper we will present an MFA for plastics in Germany, including an outlook for the future. We will first describe the methodology, followed by an analysis of the production and use of primary plastics. We will end with projections of future plastics waste and product accumulation in Germany.

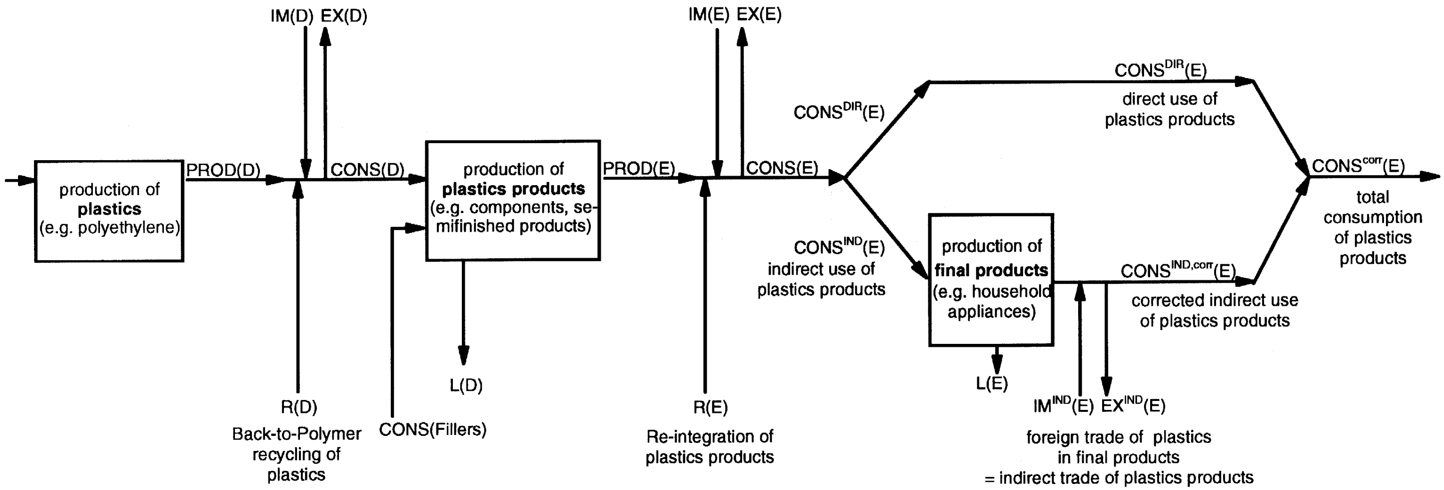
2. Methodology

Fig. 1 shows the flows connected to the production and consumption of plastics. Primary plastics (e.g. polyethylene), denoted by D in Fig. 1, are produced as virgin materials and a part is also provided by back-to-polymer recycling of post-consumer waste[2]. Moreover, primary plastics are imported and exported. Information on these physical flows is available by types of plastics [2,3] enabling the calculation of the domestic consumption of plastics according to:

$$\mathrm{CONS}(D) = \mathrm{PROD}(D) + R(D) + \mathrm{IM}(D) - \mathrm{EX}(D) \tag{1}$$

[1] All data refer to Germany including the New Federal States if not stated otherwise.

[2] In this paper we will not analyse recycling of pre-consumer waste from plastics production and processing. These flows are treated as internal loops in the respective subsystems.



carbon flows:
CONS(i) = domestic consumption of commodity i
PROD(i) = total production of commodity i
IM(i) = imports of commodity i
EX(i) = exports of commodity i
L(i) = losses & leakages of commodity i

indexes:
i = commodity, e.g. i = B = feedstock inputs, i = C = intermediates, i = D = materials and intermediates, i = E = final products

Fig. 1. A country's plastics flows from production to final consumption.

CONS(D) gives the amounts of plastics that are used to manufacture semifinished products (e.g. sheets, films), plastics components (e.g. moulded items), plastics packaging and non-plastics products (e.g. paints, adhesives). The production of these plastics products (E), which are given by national statistics, must be consistent with the consumption of primary plastics, taking into account the use of fillers (e.g. calcium carbonate), plasticizers and the production losses:

$$\mathrm{PROD}(E) = \mathrm{CONS}(D) + \mathrm{CONS}(\text{Fillers etc.}) - L(D) \tag{2}$$

By analogy with Eq. (1), the domestic consumption of plastics products, CONS(E), is determined by the amount of plastics products re-used ($R(E)$) and by imports and exports (IM(E), EX(E)). The domestic consumption of plastics products CONS(E) can be split into two parts, one which is used directly ($\mathrm{CONS}^{\mathrm{DIR}}(E)$), and one used indirectly ($\mathrm{CONS}^{\mathrm{IND}}(E)$):

$$\mathrm{CONS}(E) = \mathrm{CONS}^{\mathrm{DIR}}(E) + \mathrm{CONS}^{\mathrm{IND}}(E) \tag{3}$$

Direct use of plastics products occurs in buildings, agriculture and as simple household equipment. The remaining plastics products are integrated in final products, referred to as the indirect use of plastics, e.g. plastics packaging of food or plastics components in cars. As final products are traded, imported and exported, the plastics incorporated in the products follow the same patterns ($\mathrm{IM}^{\mathrm{IND}}(E)$, $\mathrm{EX}^{\mathrm{IND}}(E)$). Correction of the indirect use of plastics products ($\mathrm{CONS}^{\mathrm{IND}}(E)$) by these flows yields the entity $\mathrm{CONS}^{\mathrm{IND,\,CORR}}(E)$:

$$\mathrm{CONS}^{\mathrm{IND,\,CORR}}(E) = \mathrm{CONS}^{\mathrm{IND}}(E) - \{\mathrm{EX}^{\mathrm{IND}}(E) - \mathrm{IM}^{\mathrm{IND}}(E)\} - L(E) \tag{4}$$

Together with the direct use ($\mathrm{CONS}^{\mathrm{DIR}}(E)$), this gives the total domestic consumption of plastics $\mathrm{CONS}^{\mathrm{CORR}}(E)$:

$$\mathrm{CONS}^{\mathrm{CORR}}(E) = \mathrm{CONS}^{\mathrm{DIR}}(E) + \mathrm{CONS}^{\mathrm{IND,\,CORR}}(E) \tag{5}$$

In Eq. (4), $L(E)$ represents the plastics losses which occur during the manufacture of final products. Given the fact that this production step represents assembling operations, $L(E)$ is assumed to be very small and can be neglected.

All the entities in Fig. 1 refer to physical flows, i.e. they are given in mass units. In contrast to other import and export data, the plastics flows $\mathrm{IM}^{\mathrm{IND}}(E)$ and $\mathrm{EX}^{\mathrm{IND}}(E)$ cannot be derived directly from foreign trade statistics, but are calculated using a combination of physical and monetary data. The first step is to identify the sectors s where the indirect consumption of products, $\mathrm{CONS}^{\mathrm{IND}}(E)$, occurs. To this end, $x^{\mathrm{IND}}(E,s)$ is determined which represents the share of each of these products E supplied to the various sectors s. The amounts of plastics which enter and leave the country together with the goods of the respective sector s can be roughly estimated by:

$$\mathrm{IM}^{\mathrm{IND}}(E) = \sum \left\{ \frac{\$\mathrm{IM}(s)}{\$\mathrm{PROD}(s)} \times x^{\mathrm{IND}}(E,s) \times \mathrm{CONS}^{\mathrm{IND}}(E) \right\} \tag{6}$$

$$\mathrm{EX}^{\mathrm{IND}}(E) = \sum \left\{ \frac{\$\mathrm{EX}(s)}{\$\mathrm{PROD}(s)} \times x^{\mathrm{IND}}(E,s) \times \mathrm{CONS}^{\mathrm{IND}}(E) \right\} \tag{7}$$

\$PROD(s) is the value of production and \$EX(s) and \$IM(s) represent the export and import value respectively. These three entities are given in monetary terms. The underlying assumption is that the plastics intensity of a sectors (given in kg plastics per DM merchandise) is similar for domestic production, imports and exports (see below).

We compiled time series for the total domestic consumption of plastics products by groups ($\mathrm{CONS}^{\mathrm{CORR}}(E)$). The plastics products are used for a certain period of time before they are discarded as post-consumer waste. If the consumption $\mathrm{CONS}^{\mathrm{CORR}}(E)$ took place in the year j, the product E will be discarded as waste $W(E)$ after a residence time r, which is defined as the year t:

$$t = j + r(E, j) \tag{8}$$

$$W(E,t) = \mathrm{CONS}^{\mathrm{CORR}}(E, j) \tag{9}$$

To determine the residence time r of a group of products E, i.e. $r(E)$, these products are first assigned to various applications, with $y(E,a)$ representing the share of plastics product E used for the application a. Each application is characterized by a certain service period, named $r_{\mathrm{appl}}(a)$. The residence time $r(E)$ is calculated by weighting the service periods in each category of application $r_{\mathrm{appl}}(a)$ with the respective shares $y(E,a)$ used in this category:

$$r(E) = \sum_a \{r_{\mathrm{appl}}(a) \times y(E,a)\} \tag{10}$$

We assume the residence time $r(E)$ to follow a Gaussian distribution in order to account for the fact that the service period of a product varies (depending on the product group, the standard deviation was estimated between 10 and 30% of the mean). We also assume that $r(E)$ is constant within the entire time frame analyzed which may not be perfectly true due to changes in consumption patterns. Using Eqs. (8)–(10) we can calculate the amounts of waste originating from the products E, $W(E,t)$. This leads to the total amount of post-consumer waste in year t:

$$W(t) = \sum_E W(E,t) \tag{11}$$

Three factors influence the results and their reliability when correcting for imports and exports (see below).

Firstly, it is assumed that the plastics content of each category of goods is similar for domestic production, for imports and exports. This is only correct if

1. The composition of a specific product group is identical for production, imports and exports.
2. And if the amount of plastics incorporated in a certain product manufactured for the home market is identical with that of a comparable imported and exported product.

As there is no detailed information available in these areas it is impossible to test the two hypotheses.

Another source of uncertainty is that \$IM(s) and \$EX(s) on the one hand and \$PROD(s) on the other are not perfectly comparable: If we are forced to use gross values of production for \$PROD(s) then double counting may occur. Since there is no similar phenomenon with imports and exports, the factors \$IM(s)/\$PROD(s) and \$EX(s)/\$PROD(s) in Eqs. (6) and (7) tend to be too small, so it is probable that indirect net foreign trade, as given by the term $\{EX^{IND}(E) - IM^{IND}(E)\}$ in Eq. (4), is underestimated.

To determine the indirect imports and exports $IM^{IND}(E)$ and $EX^{IND}(E)$, five aggregated sectors are distinguished, i.e. vehicles/machinery, electrical appliances/electronics/precision engineering, chemical industry, food industry and distribution. The fractions $x^{IND}(E,s)$ were determined using the results of the more detailed allocation to categories of application $y(E,a)$ (see below). Financial data for the production and foreign trade of the sectors s, i.e. \$PROD(s), \$IM(s) and \$EX(s) are available from economic input/output tables as a time series covering most of the years between 1978 and 1991 [9]. Missing data were estimated by interpolation. On this basis, we calculate the correction term $\{EX^{IND}(E) - IM^{IND}(E)\}$ in Eq. (4) to amount to a total net export of 210 (1991)–350 kt (1989) which is equivalent to 3–6% of the domestic consumption of plastics products (CONS(E)). According to own estimations the majority of this is due to the two sectors vehicles and machinery.

To reduce methodological uncertainties, further detailed bottom-up analyses for indirect imports and exports would have to be performed as presented by Brahms et al. [10] for plastics packaging in the food sector. However, this is practically impossible for the large number of products and categories of application covered in our study. An alternative approach has been presented by Joosten et al. [11]. This method is based on very detailed make-and-use tables which are unfortunately not published by the German Statistics Office.

3. Empirical analysis

We started with a detailed study [12] of the manufacture of plastics products in Germany in 1989 which we extended by time series and by a model for waste generation presented in this paper. We will first analyze the manufacture of plastics products and examine applications in which they are used. Finally, we will model waste generation both for the present and the future.

3.1. Production of plastics products

Fig. 2 shows the manufacture and direct foreign trade of plastics products (E) starting from the production of primary plastics (D). The production of plastics products can be determined using two methods: a top-down and a bottom-up approach.

To apply the top-down approach, the production of plastics products is calculated from Eqs. (1) and (2). Production and foreign trade data are available in physical terms from the German Statistics Office ([2–4], personal communication with Mr. Mielke, Berlin) and the German Association of Plastics Manufacturers [13]. We use own estimates for the amount of fillers and reinforcing agents used [12], since the consumption of these materials is not monitored and producers are reluctant to provide information due to the highly competitive character of this market. Production losses only cover the amounts that are not recycled internally, but actually leave the production chain[2]; these losses are nearly negligible, amounting to approx. 1% of plastics input in this processing step [12].

In the bottom-up approach, the production volumes of individual plastics products (E) are added. Six main groups of plastics products were distinguished,

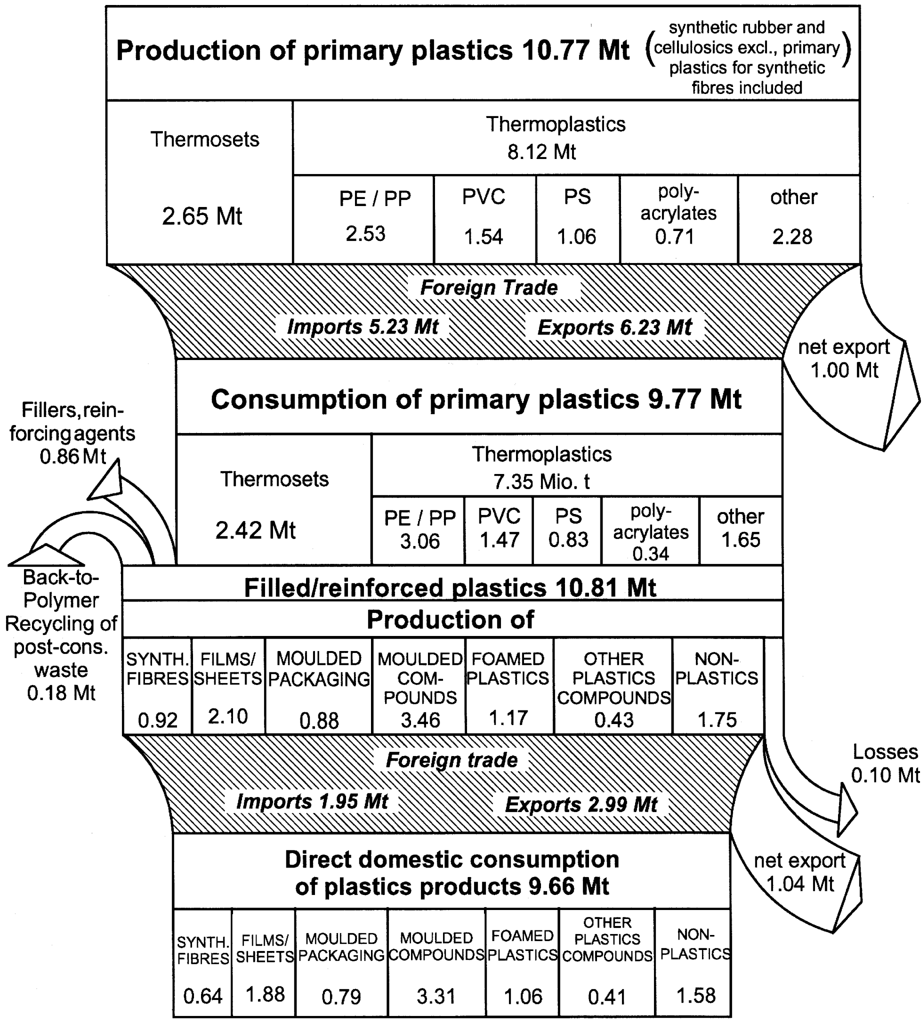


Fig. 2. Production and use of plastics in Germany in 1994 (presentation following [10]; data from [2,3,14], own estimates, own calculations).

i.e. fibres, films/sheets, moulded packaging materials, moulded components for other purposes, plastic foam products and non-plastics products (e.g. paints and adhesives). For some of these product groups, data were readily available (e.g. for fibres). For others, labour-intensive aggregation procedures were necessary (e.g. more than 70 items for the product group moulded components).

The comparison of the top-down and the bottom-up approach shows that about 96% of all plastics products can be traced on a product-by-product basis (see Fig. 2) [12]. The missing 4% of primary plastics consumption were ascribed to a rest group of plastics products ('other plastics products'). The product group 'non-plastics' will not be analyzed since it is not generally classified as part of the plastics products group, nor is it included in the definition of plastics waste which will be discussed later.

In Germany, production data for plastics products are published in physical units [2]. The sectors in the production statistics are defined on a functional basis, meaning that plastics processing outside the main sector is also covered. However, small enterprises with less than 20 employees are not included in German production statistics. Their contribution was estimated using financial data (except for fibres, due to the dominance of large enterprises). Double counting must be avoided when aggregating the individual products to form groups of plastics products.

Bottom-up aggregation enables the allocation of the total consumption of primary plastics to groups of products as given in Fig. 2. Foreign trade data was collected for these products allowing the calculation of the domestic consumption of plastics products (CONS(E)). For the group of 'other plastics products', import and export quotas were based on the average of all other products. Since production and foreign trade statistics are not perfectly compatible, this step may lead to inaccuracies on the level of product groups.

To analyze the developments over time, the material flows are also depicted as a time series (see Fig. 3). Periodic changes in the classifications of foreign trade and production statistics, and the reunification of East and West Germany lead to potential problems. Pre-1990 data for production and foreign trade in the former GDR were made available by the Federal Statistics Office in Berlin ([4], personal communication with Mr. Mielke, Berlin).

3.2. Residence times of plastics products in the economy

To obtain a better understanding of the consumption pattern, we will examine the categories of application of plastics products and the residence times in the economy. We will analyze the situation in West Germany in the year 1989. Then, we will assume that the residence times by product groups are representative for the entire period from 1976 (for long-lived products back to 1960) until and beyond 1995. West German consumption patterns have dominated in the past (due to the low share of consumption in the East) and will continue to do so in the medium term future.

The first set of results is presented in Table 1. Subgroups were formed for some of the product groups (resulting in a total of 13 groups) thus enabling a more accurate allocation. The information required to execute these two steps was taken from production statistics [2], association statistics [15,16] and from the literature

Table 1
Use of plastics products by categories of application, West Germany, 1989 (based on own calculations)

Category of application	Group of plastics products, in kt							
	Synthetic fibres	Films/sheets	Moulded packaging material	Moulded compounds	Foamed plastics	Other plastic products	Total	(%)
Vehicles and machinery	172	73	0	643	70	104	1061	15
Elec. appl., precision eng.	29	0	0	475	28	58	589	8
Packaging	0	932	510	0	0	157	1598	22
Building	57	553	0	1033	218	202	2063	28
Agriculture	29	329	0	0	0	39	397	5
Households	165	0	0	291	0	49	506	7
Furniture	165	0	0	160	90	45	460	6
Clothing	252	0	0	42	0	32	326	4
Other	0	0	152	27	45	24	248	3
Total	868	1887	662	2671	451	710	7249	100

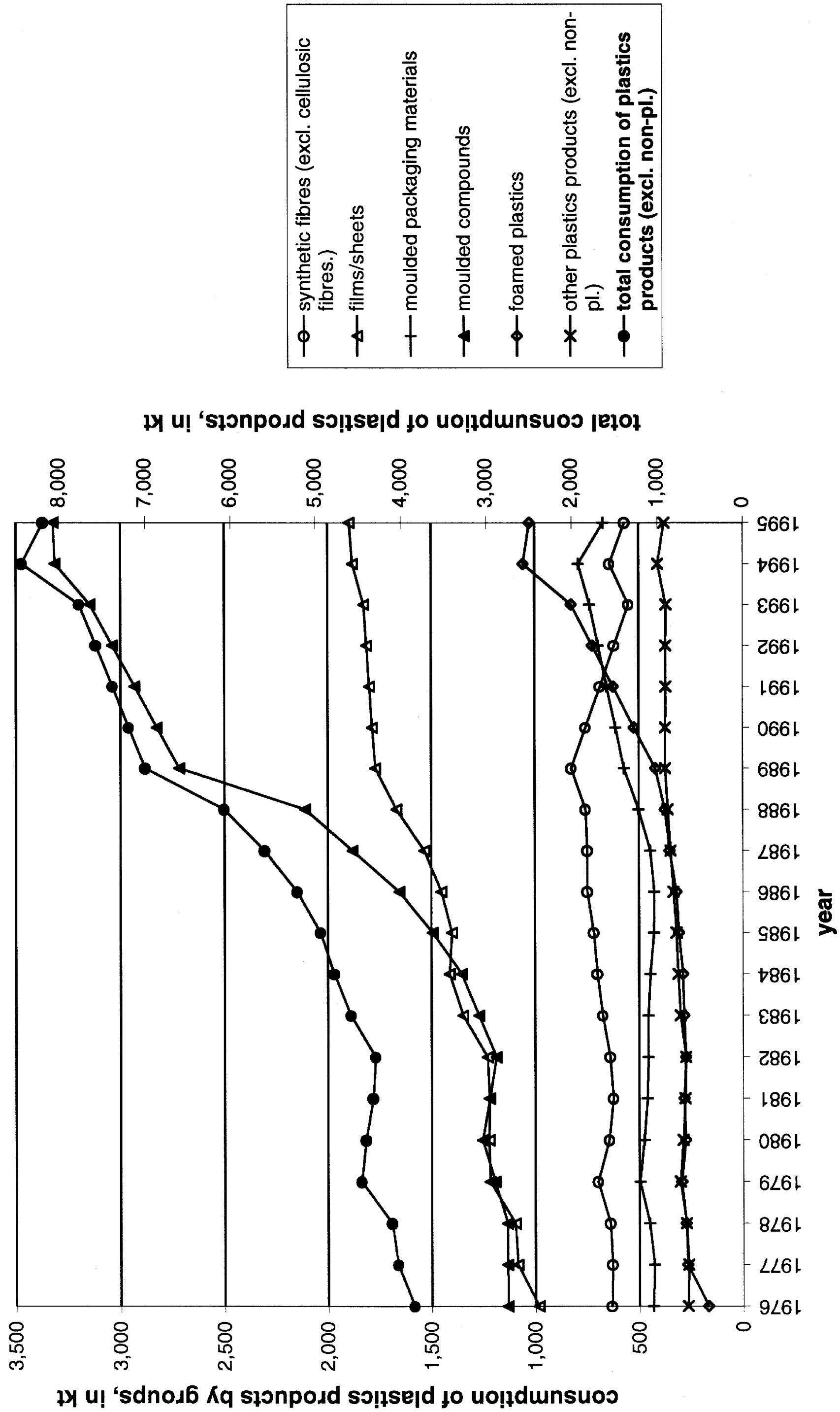


Fig. 3. Development of the consumption of plastics products (CONS(E)) in Germany, 1976–1995.

[17]. If no other information was available, we made our own estimates. From the absolute amounts given in Table 1, the shares $y(E,a)$ of plastics products E used in the various categories of application a can be determined (see Section 2).

In Table 2, the distribution of total plastics products among the categories is compared with data from other sources. Non-plastics have to be included in the comparison if they are part of the quoted data. As shown, the results of our analysis compare quite well with those of other studies.

Table 3 shows the mean service periods $r_{\mathrm{appl}}(a)$ of all the plastics goods consumed in the various categories of application. These values are estimated on the basis of literature analysis. Using this information in Eq. (10) we calculated $r(E,t)$ as listed in Table 4. As already mentioned we must assume these figures to be representative for the entire analysis period since the available data do not allow more detailed, time-dependent analyses. Neither is a distinction between former West Germany and East Germany feasible.

As Table 4 shows, the weighted average residence time over all plastics products is 14 years (1989). The distinction by ranges of residence times yields the distribution presented in Table 5. Comparable data sets from the literature [27–29] show very large deviations for the three groups of service periods indicating that a better understanding is needed.

3.3. Current waste generation

To calculate waste generation, the time series for the (corrected) total consumption

Table 2
Plastics use in West Germany by categories of application—a comparison of our results with data from other sources

Category of application	Plastics products				
	Own data analysis			Other sources	
	1989			1992	1991
	kt	% incl. non-pl.	% excl. non-pl.	[18]	[19]
Vehicles and machinery	1061	12	15	7	17
Elect appl., precision eng.	589	7	8	15	6
Packaging	1598	18	22	21	24
Building	2063	24	28	25	15
Agriculture	397	5	5	4	
Households	506	6	7	3	
Furniture	460	5	6	5	
Clothing	326	4	4		
Other	248	3	3		38
Non-plastics	1421	16		21	
Total	8670	100	100	80	100

Table 3
Mean residence times in West Germany by application categories

Field of application	Vehicles and machinery[a]	Elec. appl., precision eng.[b]	Packaging[c]	Pipes for buildings[d]	Other building comp.[e]	Agriculture[f]	Household[g]	Furniture[h]	Clothing[i]	Other
Mean residence time $r_{\mathrm{appl}}(a)$ (years)	11	10	1	50	30	2	7	10	3	8

[a] D. Pautz, 'Industrielle Ökosysteme' [20]: 10.6 years (vehicles, West Germany); Umweltbundesamt, 'Daten zur Umwelt' [21]: 10 years (vehicles); Bisio, Xanthos, 'How to manage plastics waste' [22]: 11 years (vehicles), 15 years (machinery);

[b] Zentralverband Elektrotechnik- und Elektronikindustrie (ZVEI), estimate quoted in [23]: 10 years (electrical/electronic appliances); C. Ewen, D. Chenchanna, 'Elektro- und Elektronik-schrott-Recycling' [23], own calculations: 8.7 years (electrical/electronical appl.); Bisio, Xanthos, 'How to manage plastics waste' [22]: 15 years (electrical/electronical appl.); J. Brandrup, 'Die Wiederverwertung von Kunststoffen' [24], p. 580: 8 years (household appl. and data technology), ca. 10–20 years (measurement and control), 5 years (office communication), 20 years (telecommunication);

[c] Bisio, Xanthos, 'How to manage plastics waste' [22]: <1 year; J. Brandrup, 'Die Wiederverwertung von Kunststoffen' [24], p. 546: <2 years (food packaging, bottles, vessels, boxes, films);

[d] Enquête-Kommission [25]: 50 years (pipes);

[e] Other building components. Friedl [26]: 30 years (PVC window frames); Enquête-Kommission [25]: 30 years (window frames); Bisio, Xanthos, 'How to manage plastics waste' [22]: 25 years (building);

[f] Personal communication, KTBL (Kuratorium fur Technik und Bauwesen in der Landwirtschaft), 1997: 1 year (films for silos and bundles), 2 Jahre (PP-films u. fleeces), a smaller share with 10 years (films for greenhouses, rain-water protection and for covering of liquid manure);

[g] J. Brandrup, 'Die Wiederverwertung von Kunststoffen' [24], p. 580: ca. 8 years (household appliances); p. 546: 2–10 years (household products); Bisio, Xanthos, 'How to manage plastics waste' [22]: 5 years (consumer goods);

[h] Bisio, Xanthos, 'How to manage plastics waste' [22]: 10 years (furniture);

[i] Own estimate.

Table 4
Calculated mean residence of plastics products in West Germany

Group of plastics products	Mean residence time $r(E)$ (years)
Synthetic fibres	9
Films/sheets	10
Films for packaging	1
Films for building	30
Films for agriculture, vehicles, machinery	4
Plastics sheets	30
Moulded packaging material	3
Packaging material, short life	1
Packaging material, medium life	2
Vessels/containers, medium life	8
Large containers	8
Moulded compounds	20
Pipes for buildings	50
Other moulded compounds for buildings	30
Moulded compounds for investment and consumer goods	10
Foamed plastics	20
Other plastics products[a]	14
All plastics products	**14**

[a] The mean residence time of all plastics products was assumed to be representative.

of plastics products ($CONS^{CORR}(E)$) are linked with the residence time $r(E)$ using Eqs. (8) and (11). In general, the time series we used go back to 1976 (see Fig. 3). For very long-lived products used in buildings, the data series for consumption were extrapolated back to 1960. Taking the residence times of plastics products into account, the model should yield realistic results for post-consumer waste generation starting from 1990.

Table 6 shows both the model results for post-consumer plastics waste and literature values. The literature data have to be compared to the model results given in line b) (fibres excluded). The data quoted from literature are considered to be the

Table 5
Calculated distribution of plastics products consumption as a function of residence times in the West German economy in 1989

Mean residence time $r_{appl}(a)$ (years)	Consumption of plastics products (%)
0 to ≤ 3	32
>3 to ≤ 11	39
>11	28
	100

Table 6
Model results and literature data for post-consumer plastics waste in Germany

Post-consumer plastics waste in kt	1990	1991	1992	1993	1994	1995	1996
Model results							
Plastics waste including synthetic fibres	3430	3580	3820	3990	4100	4370	4380
Plastics waste excluding synthetic fibres	2830	2950	3160	3310	3400	3640	3650
Data from literature							
Sofres [8]				3076	3322	3131	
Eco-Consultic [30]					2240[a]		

All data refer to Germany including the New Federal States and are corrected for indirect foreign trade. Data exclude waste from non-plastics.
[a] For comparison: total plastics waste including pre-consumer waste: 3010 kt [30].

most reliable ones available. The comparison shows a good correspondence between our model results and the data published by Sofres [8]. The figures determined by Eco-Consultic [30] are decisively lower. One of the reasons is that the latter do not include waste from plastics foams. Another reason is that the Eco-Consultic data are based on surveys (questionnaires, combined with projections), possibly leading to an underestimation of hidden waste streams. Moreover, our model results may be on the higher side, since we do not account for second life applications, e.g. the use of packaging containers for the storage of household items (e.g. nails) and since some components, especially in the building sector, are not removed but remain in the original place without being used any more (e.g. pipes). Due to lack of data, it is impossible to describe these developments in quantitative terms. Unfortunately, information from waste statistics [31,32] are not useful for our purposes since they provide an incomplete picture of waste plastics streams. For example, there is no recent survey on the amount of plastics in municipal solid waste.

To summarize, the discrepancies are partly caused by the different methodologies, and partly by the differences in scope. Future research is needed to understand and reduce the deviation.

3.4. Modelling future plastics accumulation and waste generation

In order to understand the dynamics of plastics waste generation, this section presents projections for the future. Unfortunately, no official forecasts on German plastics products consumption (in physical terms) are available for the longer term. We therefore composed three scenarios (see Table 7) to investigate the impact of consumption on future waste volumes and plastics stocks in economy:

1. The ‘High growth scenario’ assumes that physical consumption of plastics products increases by an average of 3.0% p.a. during the period 1994–2020; this growth rate is somewhat higher than the linear trend of the last 15 years which is equivalent to 2.3% p.a. for the period 1994–2020.
2. In the ‘Business-as-usual scenario’ (BAU), consumption increases by an average

Table 7
Three scenarios for the future consumption of plastics products in Germany

Scenario	Domestic consumption of plastics products, in kt								
	1976		1994		2005		2020		2050
High growth	3846		8436		12 600		18 200		18 200
Index (1994 = 100) (%)			100		149		216		216
Increase (% p.a.)		4.5		3.7		2.5		0.0	
Absolute increase (kt p.a.)		255		379		373		0	
Business-as-usual (BAU)	3846		8436		10 800		14 100		14 100
Index (1994 = 100) (%)			100		128		167		167
Increase (% p.a.)		4.5		2.3		1.8		0.0	
Absolute increase (kt p.a.)		255		215		220		0	
Stagnation	3846		8436		8400		8400		8400
Index (1994 = 100)	100	100	100	100					
Increase (% p.a.)		4.5		0.0		0.0		0.0	
Absolute increase (kt p.a.)		255		~0		0		0	

All data refer to Germany including the new federal states.
Data exclude consumption of non-plastic products.

of 2.0% p.a. during the period 1994–2020; this is slightly less than the linear trend of the last 15 years.
3. The 'Stagnation scenario' assumes that annual consumption stagnates at the 1994 level.

Interlinked developments—including future economic development (especially that of the plastics consuming sectors), technological progress in plastics processing, use and recycling and the substitution of other materials, e.g. steel and paper—will determine the future consumption. However, examination of these developments is outside the scope of this paper. Consequently, we assume that no major shifts will occur concerning the consumption structure of plastics products in the mid-term future.

As Williams et al. [33] showed, the specific consumption of bulk materials relative to GDP or population starts to decrease once these materials have reached their 'maturity stage'. We assume that this will occur for plastics in the longer term and that the consumption of plastics products will therefore stagnate from the year 2020 onwards in all scenarios.

We will limit our projections of waste by volume and types to the period until the year 2025. In a few cases, we will also draw some conclusions about the development until and beyond the year 2050; however, these only have the purpose of visualizing the long-term effects of the development in the preceding periods and should not be looked upon as scenario forecasts as such.

The most recent economic input–output tables are available for 1991 [9]. Therefore we cannot analyze the trend of indirect foreign trade and its impact on plastics waste in the last few years and we will neither correct for indirect imports and exports in our projections for the future. We will include synthetic fibres whenever we refer to plastics waste, but we will exclude non-plastics.

Fig. 4 presents the model results for plastics waste by products assuming a development according to the BAU Scenario. For short-lived products, like packaging materials, waste follows the development of consumption directly and stagnates soon after the year 2020. Waste from long-lived products on the other hand, e.g. from the building sector, continues to increase much longer and therefore reaches higher ratios between final and current waste levels. There is also less uncertainty associated with the projections for these products since the future development is determined by historic consumption to a larger extent than for short-lived products.

Fig. 5 shows the annual consumption of plastics products and amount of plastics waste for the three scenarios. The three upper lines represent the *consumption* of plastics products. The amount of plastics *waste* generated per year is depicted by the three lines beneath. Starting from 4.6 Mt[3] p.a. in 1995, waste increases to 6.2, 6.7 or 7.2 Mt for the three scenarios by the year 2005[4]. By 2025, the variation has

[3] As mentioned above this and the following figures are not corrected for indirect foreign trade; correction for 1995 yields a value of 4.4 Mt as presented in Table 6.

[4] For the near term future, we can compare our results to those of a study which was performed by Shell and which calculates plastics waste in Western Europe [34]. According to the Shell study, plastics waste will increase by 27% between 1995 and 2000. For the same period, our calculations indicate an increase of 21% in the stagnation scenario, of 26% in the BAU Scenario and of 30% in the high growth scenario.

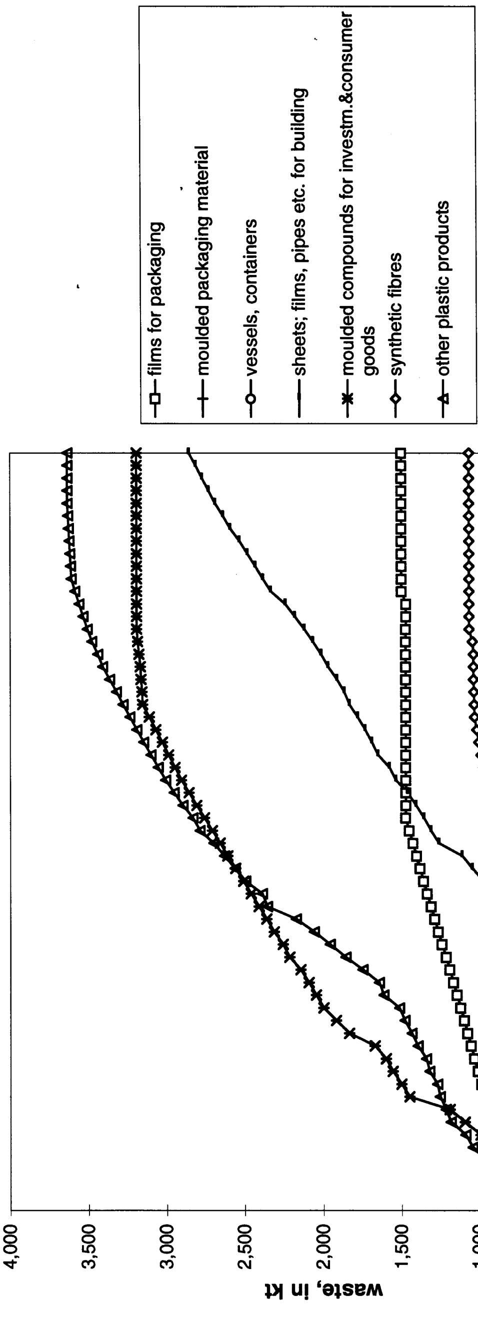


Fig. 4. Model results for plastics waste by product groups in Germany for the BAU Scenario.

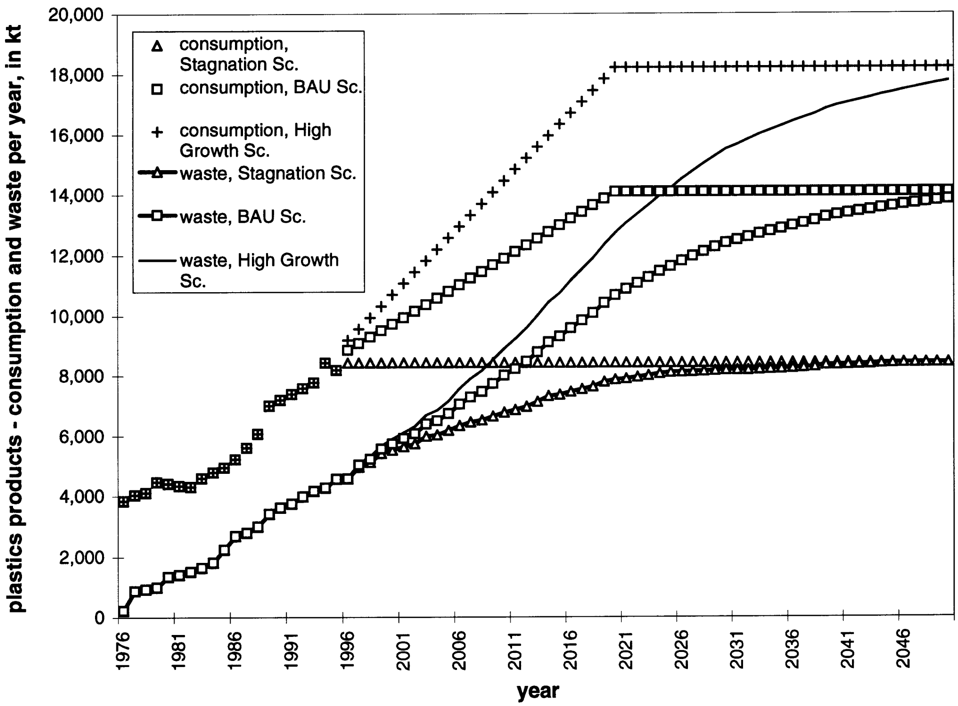


Fig. 5. Consumption of plastics products and waste per year in Germany until 2050 (based on model calculations).

increased considerably, and the values are 8.1, 11.6 and 14.2 Mt respectively. This variation shows that plastics waste could triple within 30 years. The scenarios also show that waste continues to increase for about 30 years after the consumption of plastics products has levelled off (see [10]). This is due to the high share of waste from long-lived products. The share of waste from these products will grow considerably in the next decades as Fig. 6 indicates.

Fig. 7 depicts the development of waste by types of plastics as calculated by our model for the stagnation scenario. For PVC, also literature data are available and have been included in the graph. The comparison indicates that the model provides realistic results for the main types of plastics. For waste modelling beyond the year 1995, the assumption has been made that the shares of the various types of plastics used in the manufacture of plastics products remain unchanged. However, substitution will occur among the various resins, most probably in favour of polyolefins. In spite of these limitations we conclude that polyolefins (PE, PP) will continue to be the most important fraction in plastics waste. The amounts of waste polyolefins and even more so, waste PVC will continue to rise for a long period due to the long residence times of the products (building components). Assuming a development according to the BAU Scenario, the fractions in plastics waste in 25 years' time will equal 4.7 Mt of polyolefins, 1.5 Mt of PVC and 1.1 Mt of polystyrene per year (2020).

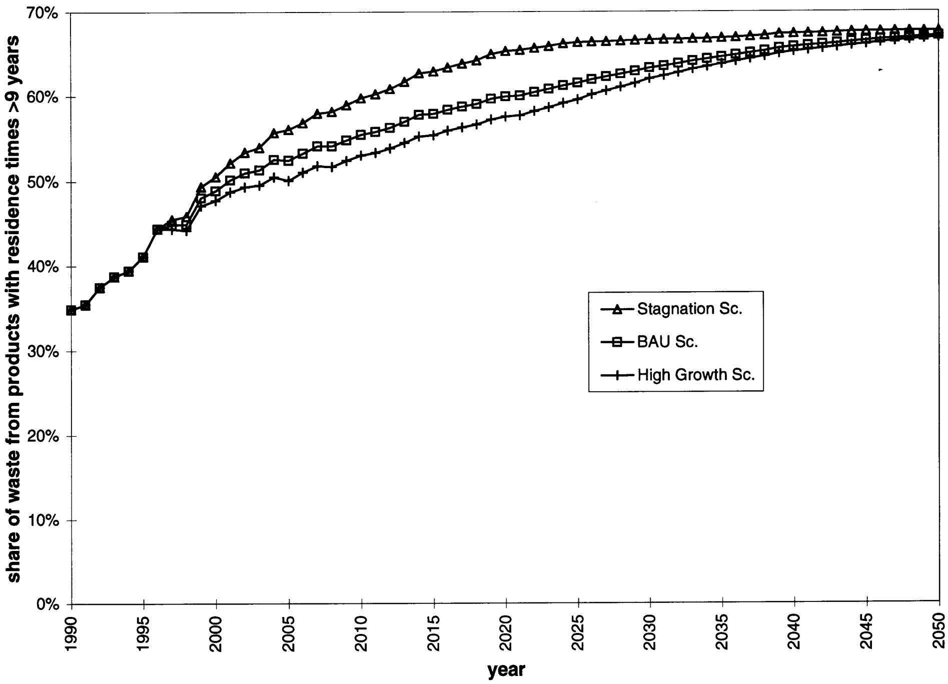


Fig. 6. Share of long-lived products in plastics waste in Germany (based on model calculations).

The respective amounts in 1995 were calculated to be 2.0 Mt (polyolefins), 0.6 Mt (PVC) and 0.5 Mt (polystyrene).

In Fig. 5, the difference between consumption curve and the waste curve equals the net annual accumulation of plastics products in the economy. This is depicted in Fig. 8 indicating that product stocks reach their maximum around the years 2045 in the stagnation scenario and beyond 2050 for the BAU and the high growth scenario.

The cumulated flows are estimated by integrating the annual values over time. Cumulated waste from the 18-year period 1976–1994 amounts to approx. 44 Mt; for the following period of 18 years stretching from 1994 to 2012 we determine approx. 105 Mt (stagnation scenario), 115 Mt (BAU scenario) and 125 kt (high growth scenario).

Fig. 9 shows the amount of plastics stocks in the economy calculated by subtracting cumulated waste from cumulated consumption for each scenario: The current stock of 72 Mt (1995)[5] increases to 125, 180 and 225 Mt in 2025 for the

[5] In 1985, the amount of plastics products stocked in the West German economy was 40 Mt according to [10] as opposed to 38 Mt for both East and West Germany according to our own model calculations. This inconsistency can be explained by the fact that the first value was calculated using a time series for the consumption of plastics products starting in 1960 whereas, for the latter, the first year considered was 1976 (except for products used in the building sector). Comparisons for West Germany only indicate that our own calculations underestimate plastics stocks by approx. 8 Mt in 1985, but this effect fades out in the subsequent years and is already non-existent in 1990.

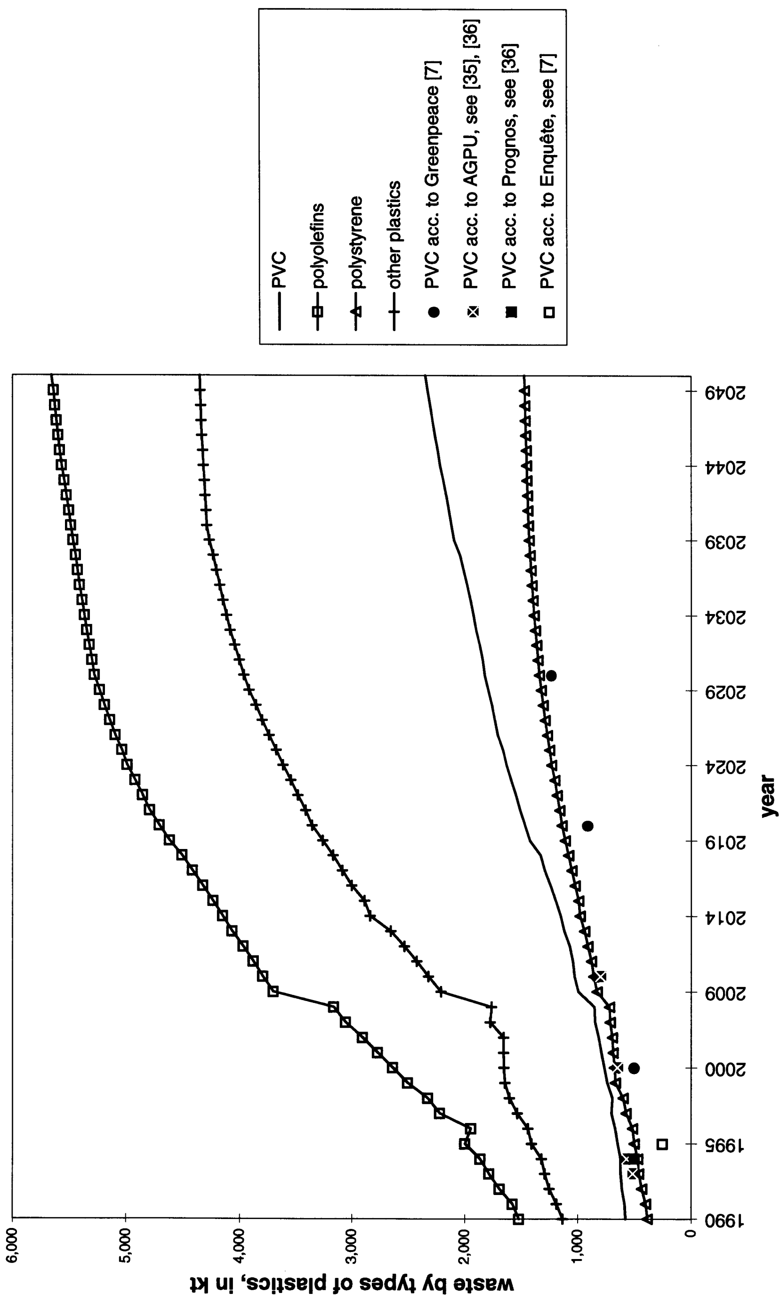


Fig. 7. Model results for waste by types of plastics in Germany for the BAU Scenario.

stagnation, the BAU and the high growth scenarios respectively. Speaking in terms of today's consumption of plastics products, the stocks are 15, 22 and 27 times as high in 2025 and they even continue to grow in the BAU and the high growth scenario.

4. Conclusions

We have developed a method to trace and simulate plastics streams in production, consumption and waste generation in the German economy. Various assumptions were made, mostly concerning material flows on a disaggregated level, i.e. the material amounts or the residence times of individual product groups. To test the accuracy of our assumptions, we compared our results with other sources wherever possible. In general, we found a good compatibility. Our comparisons also show that literature data are very often badly specified with regard to system boundaries,

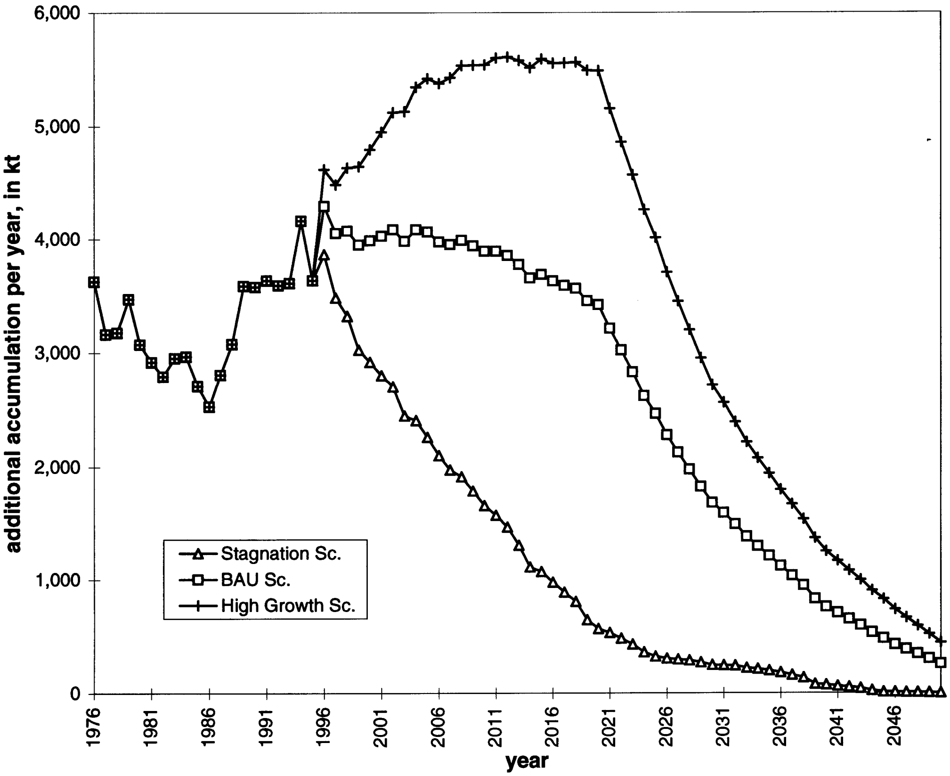


Fig. 8. Calculated net annual accumulation of plastics products in the German economy.

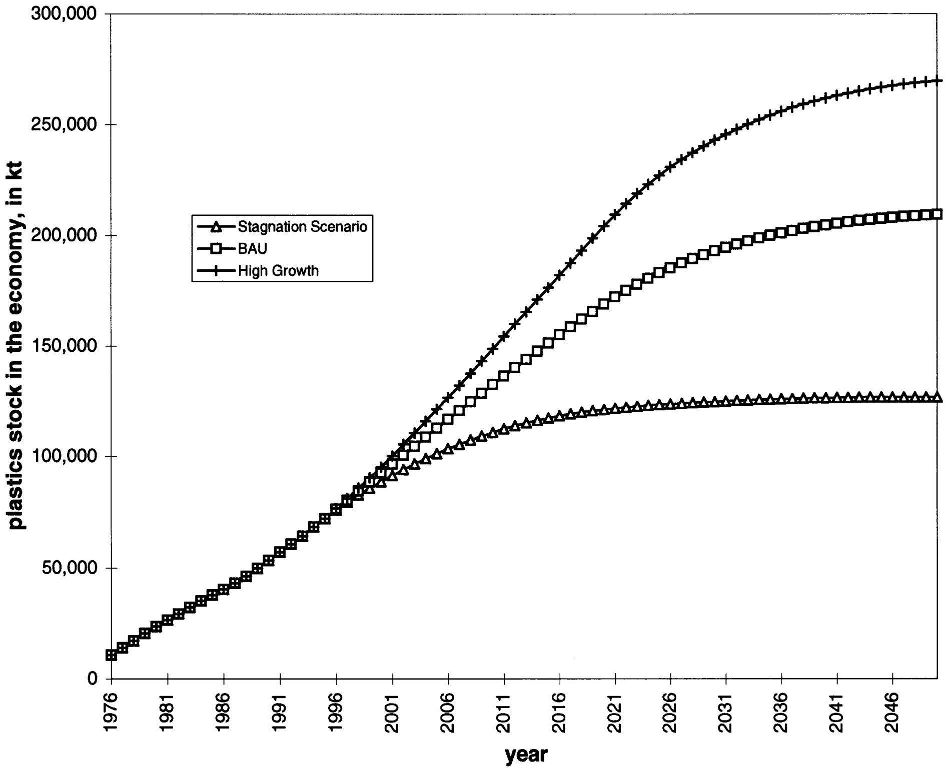


Fig. 9. Calculated stocks of plastics products in the German economy.

e.g. concerning the inclusion of non-plastics. Moreover, literature data show very large deviations in some cases, indicating a considerable lack of knowledge with regard to plastics flows in the German economy.

Increasing consumption figures of plastics products result in increasing future waste volumes. For example, total plastics wastes including synthetic fibres in the year 1995 (4.4 Mt, see Table 6) roughly equalled the consumption of plastics products in 1980. In the same period, the consumption of plastics products has increased by 86% (8.2 Mt in 1995).

For the present consumption pattern of plastics products, a weighted average of 14 years passes until the amounts consumed return as waste (see Table 4). But there is a wide range, from a few months to 50 years or more. This is the reason why waste continues to grow even if the consumption of plastics products stagnated decades earlier (see Fig. 5, stagnation scenario).

The second set of findings refers to the 'waste impact'. Depending on the future development of consumption, plastics waste will increase by 35–55% between 1995 (4.6 Mt[3]) and 2005 (6.2–7.2 Mt). Considering current growth prospects for plastics use, it is quite probable that waste figures in 2025 will be in the range of 12–14 Mt. Parallel to this development, plastics stocks in the economy will increase from roughly 70 Mt today to a steady-state value of 125 Mt (stagnation scenario) up to more than 270 Mt (high growth scenario) in the long run. The share of waste from long-lived products will continue to grow in the next decades. For polyolefins, PVC and polystyrene in plastics waste, we expect that the amounts will more than double within the next 25 years.

The expected amounts of plastics waste need not be a threat. New technologies have been developed and a number of measures have already been taken (e.g. German system DSD). As a result of these efforts, the current share of post-consumer recycling and recovery in Germany amounts to nearly 30%[6] today (1994) [30]. The future design of our waste management system is partly determined by the amount of plastics waste to be expected. As we showed, waste volumes will rise decisively (Fig. 5). More and more attention will be needed for waste from plastics use in long-lived applications (Figs. 4 and 6) and for specific waste management strategies for the most important types of plastics (Fig. 7). Further analyses are required to improve understanding of the discrepancy between the results of the survey method [30] and our model, to investigate the effect of indirect foreign trade in more detail and to disaggregate large product groups to come up with more specific conclusions. Decisions concerning the development of new waste management technologies or strategies may also be backed by similar analyses for other countries.

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